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TIME AND SPACE VARIATION OF DENSITY IN THE TROPICS.(U)

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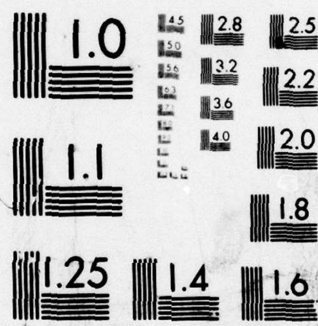

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Time and Space Variation of Density in the Tropics

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FOR THE COMMANDER

John Howard

Chief Scientist

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A preliminary analysis of the time and space variability of atmospheric density over tropical regions was developed and is presented herein. Emphasis is placed on horizontal distances out to 200 nmi (370 km) and on time periods of from 1 to 12 hr. Estimated rms differences to 200 nmi and the rms variability of density with time are provided for altitudes up to 60 km.

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1. INTRODUCTION

The behavior of atmospheric density can be a significant factor in the design and operation of reentry vehicles. *Problems related to trajectories and fusing* are particularly important, and, in order to facilitate the development of realistic specifications and evaluate vehicle performance, it is necessary to have a detailed knowledge of the time and space variations of density at altitudes up to the lower mesosphere.

A preliminary analysis of the time and space variations of density over tropical regions has been developed and is presented in this report. Emphasis is placed on changes that occur over horizontal distances out to 200 nmi (370 km) and during time periods of from 1 to 12 hr.

2. DATA

Rawinsonde observations at Kwajalein were used for this investigation, along with meteorological rocket network (MRN) observations of the thermodynamic properties and winds at Ascension I., Ft. Sherman, and Kwajalein. These data were combined with data obtained from rocket grenade experiments conducted at Ascension I., Kourou, and Natal to provide information for altitudes up to 60 km.

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The locations, observing techniques, and periods of record used in this study are shown in Table 1.

Table 1. Observation Sites

Location	Technique	Period of Record
Ascension I. (8°S, 14°W)	MRN (25-60 km) Grenade (50-70 km)	1969 - 1976 1964 - 1965
Ft. Sherman (9°N, 80°W)	MRN (25-60 km)	1969 - 1976
Kourou 5°N, 52°W)	Grenade (50-70 km)	1971
Kwajalein (9°N, 168°E)	Rawin (0-30 km) MRN (25-60 km)	Jan 1956 - Jun 1970 1969 - 1976
Natal (6°S, 35°W)	Grenade (50-70 km)	1966 - 1968

3. SPATIAL VARIATIONS

The rate of decay of the correlation coefficient between densities at two points with increasing horizontal separation is directly related to the scale of the major features of the weather patterns that cause day to day variations from the monthly means. At altitudes below 20 km, this decay in density correlation was based on an interpretation of data from studies of the spatial correlations of pressure, temperature, density, and wind for rawinsonde levels at locations between 30° and 70°N latitude.[1-3]

The correlation coefficients used for determining the spatial variability of density above 20 km are based on information contained in a 1978 COSPAR paper.[4] In that study, data taken from constant-pressure maps for 5.0-, 2.0-, and 0.4-mb levels and nearly simultaneous rocket observations at several pairs of stations were used to examine spatial correlations and wavelengths of migratory weather disturbances at altitudes up to 60 km. Based on these investigations, Cole[4] prepared Figure 1 to provide information on the decay of density correlations with distance near 60°N for altitudes up to 60 km. It is interesting to note from Figure 1 that

1. Bertoni, E.A., and Lund, I.A. (1964) Winter Space Correlations of Pressure, Temperature and Density to 16 km, AFCRL-64-1020, AD AO611002.
2. Buell, C.E. (1971) Two point wind correlations on an isobaric surface in a nonhomogeneous nonisotropic atmosphere, J. Appl. Meteorol. **10**(No. 6).
3. Buell, C.E. (1972) Correlation functions for wind and geopotential on isobaric surfaces, J. Appl. Meteorol. **11**(No. 8).
4. Cole, A.E. (1979) Review of data and models of the middle atmosphere, in Space Research XIX, Pergamon Press.

the rate of decay of the correlation coefficient decreases substantially with an increase in altitude. At 10 km, for example, zero correlation is attained at about 1100 nmi (2040 km); at 50 km, zero correlation is attained at more than twice that distance, 2400 nmi (4450 km). The 2400-nmi distance at 50-km altitude indicates that large-scale tidal and planetary waves are the dominant features at the higher levels.

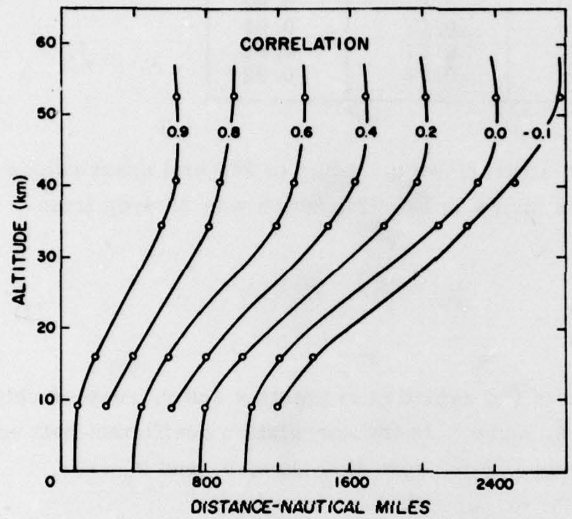

Figure 1. Decay of Density Correlations With Distance at Various Altitudes

Except for relatively rare tropical storms, such as hurricanes or typhoons, the change in the day-to-day weather patterns in the tropics is generally small. Weather systems are neither as well developed nor as intense as those over other regions. Consequently, it is assumed in this report that the rate of decay of the correlation coefficient with distance in the tropics is somewhat greater than that found at higher latitudes.[1-4] This is roughly analogous to winter-summer differences in correlation decay rates found in 25 miles over the eastern U.S. by Lund and Grantham.[5] They noted that decay rates were greater in summer than in winter for all elements studied: temperature, ceiling, sky cover, precipitation, visibility and wind speed. Based on our assumptions and on the results from the five earlier investigations for non-tropical latitudes, correlation coefficients were estimated for tropical areas at altitudes of from 10 to 60 km and for horizontal distances out to 200 nmi. Values are provided in Table 2.

5. Lund, I.A., and Grantham, D.D. (1979) Estimating the joint probability of a weather event at two locations, J. Appl. Meteorol. 18(No. 1).

Table 2. Correlation Coefficients for Horizontal Distances Out to 200 nmi (370 km) in the Tropics

Altitude (km)	Correlation Coefficient		
	50 nmi	100 nmi	200 nmi
10	0.97	0.95	0.90
20	0.98	0.97	0.92
30	0.98	0.97	0.92
40	0.98	0.97	0.92
50	0.98	0.97	0.92
60	0.98	0.97	0.92

The rms difference between densities at two points up to 200 nmi apart can be estimated by using the correlation as shown in Eq. (3), which was derived from the fundamental relationship:

$$\hat{\sigma}_{xy}^{2} = \sigma_x^{2} + \sigma_y^{2} - 2\rho_{xy}\sigma_x\sigma_y , \qquad (1)$$

where σ_x^2 and σ_y^2 are the variances of the densities at points x and y, respectively, σ_x and σ_y are the standard deviations, and ρ_{xy} is the correlation coefficient between the densities observed at points x and y. For short distances, σ_x and σ_y are assumed to be equal, reducing Eq. (1) to

$$\hat{\sigma}_{xy}^{2} = 2\sigma^{2}(1 - \rho_{xy}) \qquad (2)$$

and

$$\hat{\sigma}_{xy} = \sigma\sqrt{2(1-\rho_{xy})} , \qquad (3)$$

where $\hat{\sigma}_{xy}$ is the estimated rms difference between densities at two points, x and y, and σ is the observed standard deviation of the day-to-day variations of density around the monthly mean values. The σ is assumed to be the same for locations up to 200 nmi apart. The $\hat{\sigma}_{xy}$, plus any difference in the mean monthly densities at x and y, can be used to determine the distribution of the differences in the densities at the two locations.

The standard deviations of the observed day-to-day variations around monthly mean densities at Kwajalein are given in Table 3 as percentages of the monthly means. Values are provided in 5-km intervals from 10 to 60 km for January, April, July, and October, and are based on the Kwajalein data listed in Table 1. The standard

deviations are nearly identical to published values at two other MRN tropical locations: Ft. Sherman and Ascension I. The standard deviations of density at 18 km are shown because they deviate from the overall pattern. The relatively large values at 18 km are associated with day-to-day variations in the height of the tropopause, which normally is found between 16 and 18 km in the tropics. An example of the vertical profile of the standard deviations of density for January at Kwajalein is shown in Figure 2. The resulting estimates of rms differences in density over horizontal distances of 50, 100, and 200 nmi are shown in Table 4 for altitudes up to 60 km during the four midseason months.

Table 3. Standard Deviations (percent of mean) of Day-to-Day Variations of Densities Around Mean Monthly Values for the Midseason Months in the Tropics

Altitude (km)	January (%)	April (%)	July (%)	October (%)
10	0.4	0.4	0.4	0.4
15	0.6	0.5	0.7	0.7
18	2.5	1.7	1.5	1.7
20	1.4	1.4	1.2	1.2
25	1.4	1.4	1.2	1.3
30	1.5	1.5	1.4	1.5
35	1.7	1.5	1.5	1.8
40	2.0	2.2	2.4	2.2
45	2.3	2.0	3.0	2.6
50	2.8	2.7	3.6	2.7
55	3.3	2.8	4.2	3.9
60	4.2	3.3	5.0	4.1

Mean monthly differences in density between 0° and 15° latitude were calculated from the Tropical[6] and Air Force Reference Atmospheres.[7] The estimated mean monthly latitudinal density gradient (the percentage change with distance) ranges from 0.01 percent to roughly 0.3 percent per 100 nmi. Gradients for the midseason months at altitudes up to 60 km are shown in Table 5. Tabular values at a few levels may be unevenly distributed with altitude and season, since density (as well as temperature and pressure) gradients normally are quite small in tropical regions.

6. Cole, A.E., and Kantor, A.J. (1975) Tropical Atmospheres, 0 to 90 km, AFCRL-TR-75-0527, AD AO19940.

7. Cole, A.E., and Kantor, A.J. (1978) Air Force Reference Atmospheres, AFGL-TR-78-0051, AD AO58505.

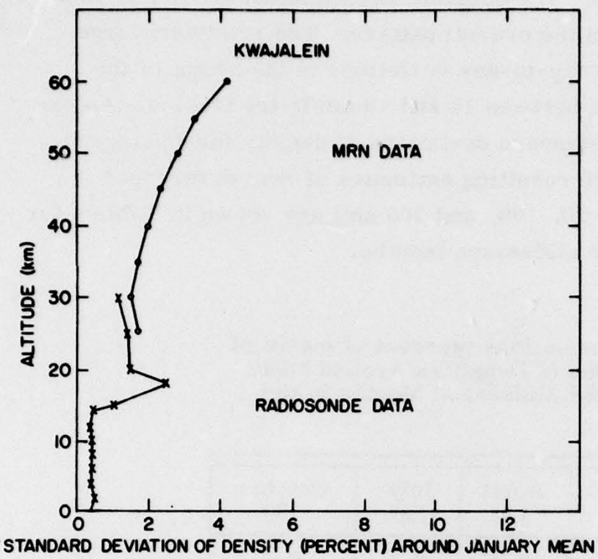

Figure 2. Variability of Density Around the January Mean at Kwajalein

Table 4. Estimated rms Differences (percent of mean) Between Densities at Locations 50, 100, and 200 nmi Apart During the Midseason Months in the Tropics

Altitude (km)	January 50 nmi	January 100 nmi	January 200 nmi	April 50 nmi	April 100 nmi	April 200 nmi	July 50 nmi	July 100 nmi	July 200 nmi	October 50 nmi	October 100 nmi	October 200 nmi
10	0.10	0.13	0.18	0.10	0.13	0.18	0.10	0.13	0.18	0.10	0.13	0.18
15	0.13	0.17	0.25	0.11	0.14	0.21	0.16	0.20	0.30	0.16	0.20	0.30
18	0.50	0.61	1.00	0.34	0.42	0.68	0.30	0.37	0.60	0.34	0.42	0.68
20	0.28	0.34	0.56	0.28	0.34	0.56	0.24	0.29	0.48	0.24	0.29	0.48
25	0.28	0.34	0.56	0.28	0.34	0.56	0.24	0.29	0.48	0.26	0.32	0.52
30	0.30	0.37	0.60	0.30	0.37	0.60	0.28	0.34	0.56	0.30	0.37	0.60
35	0.34	0.42	0.68	0.30	0.37	0.60	0.30	0.37	0.60	0.36	0.44	0.72
40	0.40	0.49	0.80	0.44	0.54	0.88	0.48	0.59	0.96	0.44	0.54	0.88
45	0.46	0.56	0.92	0.40	0.49	0.80	0.60	0.73	1.20	0.52	0.64	1.04
50	0.56	0.69	1.12	0.54	0.66	1.08	0.72	0.88	1.44	0.54	0.66	1.08
55	0.66	0.81	1.32	0.56	0.69	1.12	0.84	1.03	1.68	0.78	0.96	1.56
60	0.84	1.03	1.68	0.66	0.81	1.32	1.00	1.22	2.00	0.82	1.00	1.64

Table 5. Mean Monthly Latitudinal Density Gradients (percent change per 100 nmi) in the Tropics

Altitude (km)	January Gradient (%)	April Gradient (%)	July Gradient (%)	October Gradient (%)
10	0.01	0.02	0.03	0.04
15	0.15	0.17	0.08	0.05
20	0.12	0.23	0.08	0.06
25	0.04	0.14	0.10	0.14
30	0.26	0.13	0.14	0.21
35	0.13	0.22	0.16	0.23
40	0.03	0.16	0.16	0.20
45	0.14	0.01	0.17	0.21
50	0.11	0.09	0.12	0.20
55	0.08	0.12	0.04	0.27
60	0.09	0.04	0.10	0.25

For a given month, the rms density differences provided in Table 4 may be considered to represent variability around the mean monthly gradients given in Table 5. However, mean monthly longitudinal gradients remain near zero over tropical areas.

As an example, the north/south gradient at 30 km in July, which is equalled or exceeded 2.5 percent of the time, can be calculated for 200 nmi from the appropriate rms difference in Table 4 (0.56) and twice the mean monthly 100-nmi gradient in Table 5 (0.14×2). Assuming a Guassian distribution, the resulting density gradient exceeded 2.5 percent of the time would be approximately 2 standard deviations, 2×0.56, plus the mean gradient, 0.28, or 1.4 percent.

To further verify the correlation coefficients given in Table 2, the geostrophic wind relation was used to obtain estimates of pressure gradients associated with wind speeds equalled or exceeded approximately 16 percent of the time (1 standard deviation in a Gaussian distribution). Analyses of rocket data[4] and radiosonde data[1] have shown that the rate of decay of density correlation between two points with increasing horizontal separation is approximately the same as that for pressure height at altitudes up to 60 km. Pressure-height correlations derived from wind data at the nearest independent station, Barking Sands, Hawaii (22°N), are compared with the density correlations adopted from density data at Kwajalein, Table 6, for points 100 nmi apart at 30, 40, 50, and 60 km.

Table 6. Pressure-Height Correlation Coefficients From Wind Data vs Density Correlation Coefficients From Table 2 for Locations 100 nmi Apart

Altitude (km)	January	April	July	October	Average	Table 2
30	0.994	0.999	0.926	0.988	0.98	0.97
40	0.995	0.999	0.952	0.991	0.98	0.97
50	0.995	0.998	0.970	0.986	0.99	0.97
60	0.977	0.996	0.992	0.986	0.99	0.97

The two sets of correlation coefficients are in good agreement, with the average wind-based values only slightly larger than those derived from density data. Since the wind-based correlations were taken from Barking Sands at 22°N, a contributing factor to these small differences is the previously mentioned greater correlation decay rates typical of the lowest latitudes. These slight differences, however, are not significant in determining spatial variability of density, particularly in tropical areas where day-to-day and spatial variations are normally small.

4. TIME VARIATIONS

The estimated rms variability of density with time for 1 to 12 hr is shown in Table 7 along with rms observation errors for altitudes up to 60 km.

Table 7. Estimated rms Variations of Density With Time (percent of monthly mean) for Altitudes 10 to 60 km in the Tropics

Altitude (km)	rms Obs Error (%)	Time Lag (hr) 1	2	4	6	8	12
10	0.2	0.2	0.2	less than 1 percent			
15	0.2	0.2	0.3	less than 1 percent			
20	0.3	0.6	0.8	1.0	1.2	1.3	1.3
30	0.5	0.7	1.0	1.4	1.8	1.9	1.8
40	1.0	1.1	1.2	1.6	2.0	2.2	2.0
50	1.6	1.7	1.8	3.0	4.4	5.0	5.5
60	1.9	2.0	2.2	3.2	4.0	4.4	4.8

At altitudes below 20 km, density variations were determined from Eq. (3), using correlation coefficients of 0.95 and 0.85 for 1-hr and 2-hr time lags, and the standard deviations around the monthly means given in Table 3. These correlations are considered conservative for tropical regions, since the indicated decay in correlation with time is considerably larger than that found at midlatitudes.[8] In addition, an analysis of radiosonde observations taken at Kwajalein four times daily (0500, 1100, 1700, and 2300 UT) from March through July 1962,[9] indicates no significant diurnal density variations at levels up to 30 km. Because rms day-to-day variations around the monthly means for any time of day are less than 1 percent below 20 km (except near 18 km) and there is no apparent diurnal variation, the rms variations for time lags of from 4 to 12 hr are given in Table 7 as "less than 1 percent" for altitudes below 20 km.

Estimates of the rms variability of density with time for altitudes above 20 km are based on MRN observations from Ascension I., Ft. Sherman, and Kwajalein and on grenade experiments conducted at Ascension I., Kourou, and Natal. Since the diurnal density oscillation is larger than the day-to-day variations due to synoptic changes at these altitudes in the tropics, only one set of values is given in Table 7 for all months. Small seasonal changes (in the magnitude of the diurnal oscillation) above 30 km could result in slight differences in the values provided for time lags of from 4 to 12 hr. At these altitudes, the amplitude of the diurnal oscillation of density (based on grenade, sphere, and thermistor measurements at tropical locations) is in general agreement. However, the phase (time of maximum) differs by several hours. For example, Figures 3 and 4 both show diurnal amplitudes of nearly 4 percent of the mean at 50 km at Ascension I. and Kourou, whereas the phases are some 3 hr apart. Figure 3 is based on a harmonic analysis of a series of 24 MRN observations at Ascension I. taken over a 48-hr period on 11 to 13 April 1966; Figure 4 is based on a similar analysis of a series of rocket grenades fired at Kourou on 19 to 22 September 1971. Both sets of data confirm the fact that in the tropics an observation taken 24 hr earlier provides a better estimate of the current density at these levels than one that is only 12 hr old.

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8. Nee, P.F. (1964) Hourly Variability of Density at Radiosonde Heights, J. Appl. Meteorol. 3(No. 2).

9. Crowley, J.D., and Sandlin, J.R. (1964) A Summary of Kwajalein Atoll Upper Atmosphere Measurements and Techniques, MIT Lincoln Laboratory Project Report PPP-17 (PRESS).

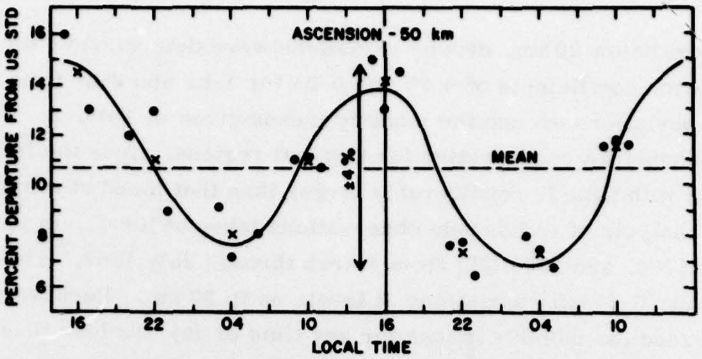

Figure 3. Diurnal Density Variation at Ascension I. Dots are observations, X's are 3-hour averages, and the curve is the computed diurnal cycle

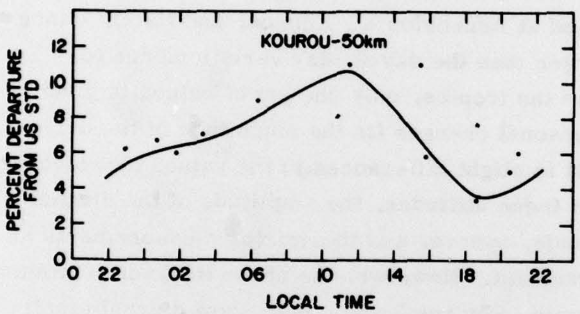

Figure 4. Sum of the First Two Harmonics of the Daily Density Distribution at Kourou. Dots are observations, and the curve is the computed cycle

5. SUMMARY AND CONCLUSIONS

A preliminary analysis of the time and space variability of density over tropical regions has been developed in this report, affording a means to determine density changes that occur over distances out to 200 nmi and over time periods up to 12 hr.

The rms differences between density at locations 50, 100, and 200 nmi apart are provided in Table 4 for altitudes up to 60 km. These rms values are estimates of the day-to-day variability of the mean density gradients given in Table 5.

The rms variability of density for time periods from 1 to 12 hr is provided in Table 7, along with estimated observation errors for altitudes up to 60 km. Values were determined using autocorrelation theory and an analysis of the diurnal variations of density.

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1. Bertoni, E.A., and Lund, I.A. (1964) Winter Space Correlations of Pressure, Temperature and Density to 16 km, AFCRL-64-1020, AD AO611002.

2. Buell, C.E. (1971) Two point wind correlations on an isobaric surface in a nonhomogeneous nonisotropic atmosphere, J. Appl. Meteorol. **10**(No. 6).

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